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An Optimization Approach for the Inverse Kinematics of a Highly Redundant Robot

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Abstract. This paper describes a robot with 12 degrees of freedom for pick-and-place operations using bricks. In addition, an optimization approach is proposed, which determines the state of each joint (that establishes the pose for the robot) based on the target position while minimizing the effort of the servomotors avoiding the inverse kinematics problem, which is a hard task for a 12 DOF robot manipulator. Therefore, it is a multi-objective optimization problem that will be solved using two optimization methods: the Stretched Simulated Annealing method and the NSGA II method. The experiments conducted in a simulation environment prove that the proposed approach is able to determine a solution for the inverse kinematics problem. A real robot formed by several servomotors and a gripper is also presented in this research for validating the solutions.

Keywords: Robot Manipulators. Pick-and-Place. Multi-objective Optimization.

1 Introduction

Architectural designs are increasing its complexity and its construction are becoming more and more difficult to implement. The awkwardness of placing components (typically bricks) fulfilling the design requirements can be solved resorting to robotics manipulation. An example of a non-standard architectural construction is presented in Figure 1.

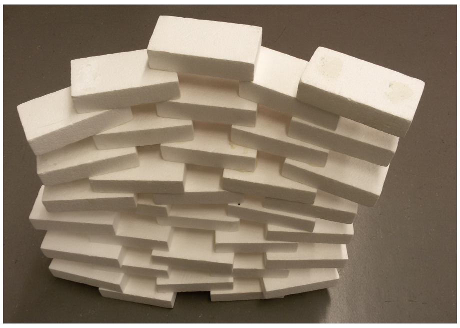

Fig. 1. Example of non-standard architecture.

There are several methods already available in the market for assembling this type of structures: on the one hand, well known industrial manipulators can be used for pick-and-place operations. These manipulators have been used for several years in industrial environment and presents usually 6 degrees of freedom (6-DOF). They are an expensive solution to develop architectural arts prototypes.

On the other hand, a novelty approach based on a cable-driven robot was recently presented in [11]. The approach based on cable driven robots appears to be an interesting solution because its construction is relatively simple and inexpensive (multiple cables attached to a mobile platform) and they are easy to transport, assembly and disassemble in different construction sites due to the lightweight of the cables. Moreover, it provides large workspace, high payloads and reliable stiffness in lateral directions under external disturbances [12].

One of the main drawbacks for the cable robots applied to the architectural arts are the collision of the suspended cables within the art. A collision avoidance system is a strong possibility to avoid this type of situations however, there are situations without a proper solution. This paper presents a preliminary approach based on a 12-DOF robot manipulator that solves the collision problems. The robot is composed by an amount of servomotors installed in a consecutive and perpendicular manner which makes it possible to place the end-effector in a desired (x, y, z) position with a $(pitch, roll, yaw)$ orientation however, the angle for each joint must be determined. By this way, the inverse-kinematics complex model can be avoided using a physics engine (open dynamics engine - [19]).

In fact, the inverse kinematics mathematical model for the proposed robot (12 DOF manipulator) is too hard to find. Instead, an optimization approach can be used to determine the posture of robot that is required for the end-effector reach the target position while minimizing the servomotors effort. This work presents an optimization approach that uses a simulation model to find the state of each joint and to establish the pose of the robot. So, a multi-objective optimization problem was defined in order to minimize the euclidean distance to the target and the servomotors effort. To solve it, two numerical optimization methods were proposed: the first, combines the Scalarization Method with Stretched Simulated

Annealing method and, the second use the well known NSGA II method for multi-objective optimization.

Moreover, a preliminary but realistic implementation of the robot is presented. This real prototype allows to validate the proposed optimization approach.

The paper is organized as follows: the related work about hyper-redundant robots and cable-driven robots are presented in Section 2 and Section 3 presents the robot model (direct and inverse kinematics). Section 4 addresses the optimization methods and algorithms used for this approach. Results are presented in Section 5 where the proof of the concept for this approach can be verified. Finally, major conclusions of this work are discussed in Section 6 where the future work direction is also pointed out.

2 Related Work

Hyper-redundant robot are used in many areas such as: Industrial inspection [7], aquatic environment [22], surgery [3], and etc. This systems offer many independent degrees of freedom and snake robots, elephant trunk robots, serpentine robots are some of representative cases. In related literature many different hyper-redundant robot are built with different principles.

One of the must approach to build a hyper-redundant robot is connecting rigid links via actuated revolute joint in a join. Another approach is parallel mechanism to connect several links together [23]. Other Hyper-redundant robot have different mechanical solutions: In [14] is used cylinder rubber pieces to construct snake robot joins, an elephant trunk robot is built in [21] features a segmented 'backbone' with a total of 32 degrees of freedom. Actuation is provided via a series of tendons routed through the structure. A slim robot were build in [13] this looks like a snake robot and composes units can stretch, shrink and bend actively is used to inspection of pipelines in plants. In this work the authors propose a new concept (bridle drive). Each unit has a bridle bellows composed of a large caliber bellows and wire lock system. A good review of the prior work had been presented in [17].

One of the major problems to solve in systems with many degrees of freedom is the resolution of inverse Kinematics. To solve inverse Kinematics there are several approaches, which can be divided into three main categories: algebraic [16] (Nonlinear optimization, Jacobian pseudo inverse,..), evolutionary computation [8] (Fuzzy logics, Artificial Neural Network, Genetics Algorithm ,..) and geometric approach [9].

Cable-driven robots, also known as cable-array or cable suspended robots, control an end-effector using multiple actuated cables [1, 20]. Cables are controlled usually by a positioning system that actuates in motors for rolling and unrolling cables. These robots are capable of performing many manipulation tasks and they have several conveniences over typical robotic manipulators [5]: a smaller number of moving parts, a lower level of visual intrusion [6], a larger working area and a higher payload ratio relative to the robots weight. On the other hand, cable interferences, inaccuracies at the end-effector due to cable stretch, and the limited force in the downward directions are some the disadvantages of cable-driven robot [20]. Currently, there is a small number of cable-driven robotic systems available on the market of sports and entertainment [1], namely, the SkyCam [18] and the Cablecam [2].

3 Robot Model

This section demonstrates the kinematics model of the robot that is proposed in this research, see Figure 3. As can be noticed in Figures 2 and 3, the robot has 12 DOF since it is formed by 12 servomotors placed in a consecutive and perpendicular manner.

3.1 Kinematics Model

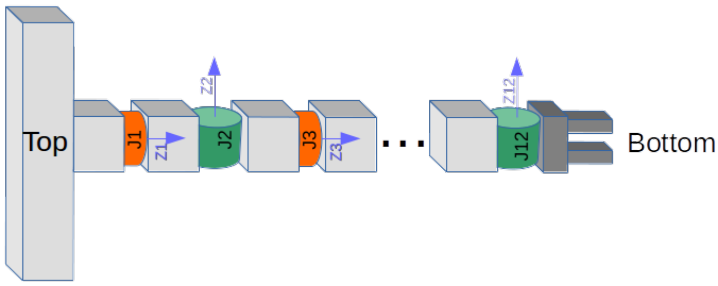

Fig. 2. Joint representation for the kinematics model of the robot.

The Denavit and Hartenberg (DH) is a methodology that gives the standard kinematics characterization for robotic manipulators. It resorts to the nature of the joint (revolution or prismatic) and makes it possible to describe the final position (and orientation) of the robotic-arm based on the joint configuration (its the value).

According to the frames described in Figure 2, the DH parameters of the proposed robot are depicted in Table 1.

Table 1. Denavit-Hartenberg parameters of a 12 DOF robotic arm, where a_i is the distance between the origin of the frame o_i and z_{i-1} (is represented in blue on Figure 2), α_i is the orientation between z_i and z_{i-1}, d_i is the distance between the x-axis of segment i and the origin o_{i-1}, and finally, θ_i is the orientation between x_i and x_{i-1}.

i-link	a_i	α_i	d_i	θ_i
0	0	0^o	0	0^o
1	0	0^o	0	θ_1^*
2	a_1	$+90^o$	0	θ_2^*
3	a_2	-90^o	0	θ_3^*
4	a_3	$+90^o$	0	θ_4^*
...	...	...	...	...
12	a_{11}	$+90^o$	0	θ_{12}^*

The transformation matrix between the frames i and $i-1$ can be defined as:

$$
{}^{i-1}T_i = \begin{bmatrix} c_{\theta_i} & -s_{\theta_i}.c_{\alpha_i} & s_{\theta_i}.s_{\alpha_i} & a_i.c_{\theta_i} \\ s_{\theta_i} & c_{\theta_i}.c_{\alpha_i} & -c_{\theta_i}.s_{\alpha_i} & a_i.s_{\theta_i} \\ 0 & s_{\alpha_i} & c_{\alpha_i} & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}
$$

In this way, it is possible to obtain the forward kinematics model of the robotic-arm in equation 2, and by considering the transformations matrices of the successive links (that can be defined through equation 1 and the parameters of Table 1). As can be noticed, this equation gives a single solution for the final position of the robotic-arm (end-effector) given the values of θ_i of each i joint.

$$
{}^0T_{12} = \prod_{i=0}^{11} ({}^iT_{i+1}) \tag{2}
$$

3.2 The Problem of Inverse Kinematics

Although the solution of the kinematics model be straightforward, the same cannot be said for the inverse kinematics model: when a final position (orientation) is desired and the values of each joint (θ_i) must be determined.

The inverse kinematics can or not have a single solution (or even multiple solutions). In some cases, a unique solution can be obtained by the mathematically considerations or motion constraints (360^o of joint revolution is usually not possible) however, the problem is not solvable in an efficient or close-form, which justifies the development of iterative techniques for controlling the manipulators.

For a higher number of DH parameters of a specific robotic-arm, higher is the complexity of the inverse kinematics model. In real applications, the highest number of DOFs that can be found in robotic-arms is usually 6 because the inverse kinematics problem turns it into a redundant system if more DOF is considered, see equation 3.

$$^{0}T_{12} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} =^{0} T_1(\theta_1).^{1}T_2(\theta_2).^{2}T_3(\theta_3)...^{11}T_{12}(\theta_{12}) \tag{3}$$

where r_{kl} is the rotation and p_w is the position information, where $k, l \in \{1, 2, 3\}$, and $w \in \{x, y, z\}$. The inverse kinematic of the first and last joint (θ_1 and θ_{12}) can be found in equations 4 and 5 (respectively) as a function of the known elements of equation 3.

$$\left[^{0}T_1(\theta_1)\right]^{-1}.^{0}T_{12} =^{1} T_2(\theta_2).^{2}T_3(\theta_3)...^{11}T_{12}(\theta_{12}), \tag{4}$$

$$\left[^{0}T_1(\theta_1).^{1}T_2(\theta_2).^{2}T_3(\theta_3)...^{10}T_{11}(\theta_{11})\right]^{-1}.^{0}T_{12} =^{11} T_{12}(\theta_{12}). \tag{5}$$

These two equations focus in only two joints (which can be extended to the others) however, they depict the complexity of the inverse kinematics problem since it requires to solve 12 simultaneous nonlinear equations, considering $r_{11}, r_{12}, ..., r_{33}, p_x, p_y, p_z$ and the fixed link parameters.

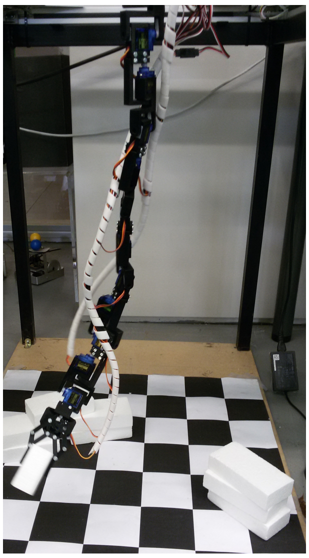

Fig. 3. The proposed robot with 12 DOF in a pick-and-place operation.

4 Optimization Procedure

The presented optimization problem requires a multi-objective approach where it is necessary to create a path to the desired position (inverse kinematics) while minimizing the maximum effort of the servomotors. Simulation environment runs the X solution and returns the euclidean distance combined with orientation (EDO) of the end-effector (f_1). Maximum effort for servomotors (f_2) is also computed as a variable to be minimized.

In this work two global stochastic optimization methods are used. The Stretched Simulated Annealing (SSA) is a global optimization method for single-objective optimization. This method was combined with scalarization method to solve the problem. The NSGA II is a popular method based on genetic algorithm for multi-objective optimization.

4.1 Stretched Simulated Annealing

The multi-objective problem was formulated as a single-objective optimization problem using the scalarization method and it was used the Stretched Simulated Annealing (SSA) to solve the following resulting problem

$$\begin{aligned} \min\ & w_1 f_1 + w_2 f_2 \\ s.t.\ & w_1 + w_2 = 1 \\ & w_1, w_2 \geq 0. \end{aligned}$$

The SSA method is a well known global optimization method based on simulated annealing and on stretched technique. More details about the SSA method can be found on [15].

4.2 NSGA II - Multi-objective Genetic Algorithm

NSGA-II is a popular non-domination based genetic algorithm for multi-objective optimization. It is a very effective algorithm that incorporates elitism and no sharing parameter needs to be chosen a priori. The NSGA II is discussed in detail in [4].

5 Numerical Results

The numerical results were obtained using a Inter Core i7-2600 CPU 3.4 GHz with 8.0 GB of RAM.

The SSA and NSGA II methods were implemented in MatLab environment [10]. For stop criteria it was considered the maximum number of function evaluations equal to 5000. The optimal set given by SSA method can be observed in Figure 4.

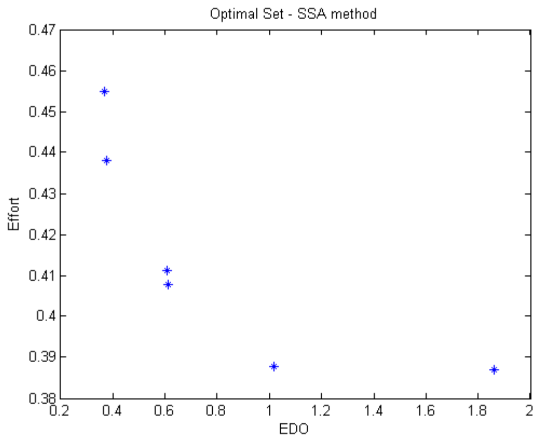

Fig. 4. Optimal set given by SSA method.

The minimum value founded by SSA method for the EDO it was 0.3694 needing 0.4549 of maximum effort from servomotors.

The optimal set given by NSGA II method is presented in Figure 5.

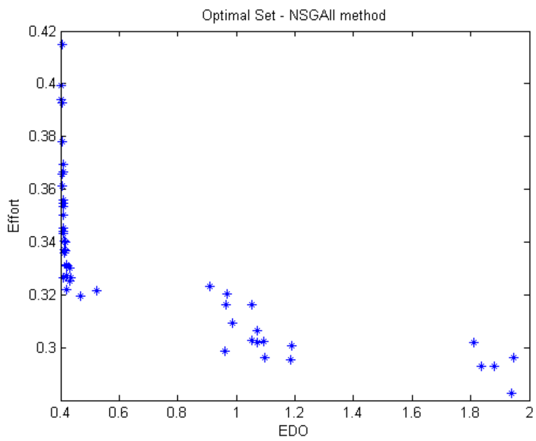

Fig. 5. Optimal set given by NSGA II method.

The minimum value for the EDO founded by NSGA II method was 0.4020 needing 0.3993 of servomotors maximum effort.

To compare the solutions obtained by the two methods it was used the measure $M = 0.75f_1 + 0.25f_2$.

The best value was obtained using the NSGA II method with value 0.3877 (considering $f_1 = 0.4080$ and $f_2 = 0.3266$). The best solution obtained by SSA method was $M = 0.3900$ considering the solution $f_1 = 0.3694$ and $f_2 = 0.4549$.

It is possible to conclude that SSA method provides the best solution considering the EDO value and the NSGA II method provides the best solution in the terms of measure M.

6 Conclusions and Future Work

The research presented in this paper introduces the *Tentacle Robot* which is a 12 DOF robot. It can be used to pick and place operations and was developed having in mind Non-Standard Architecture and Construction parts. Robot pose can be computed resorting to optimization techniques that allows to avoid inverse kinematics complex problems. About the numerical optimization methods used, the best value was obtained using NSGA II method but the SSA method provided the best value for the EDO value.

As future work, the influence of an obstacle avoidance algorithm will be studied, with the purpose of avoid collision between robot body and objects parts. Other numerical method can be used to try to improve the obtained solutions.

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